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INTELLIGENCE TRANSLATION

THE PROBLEM OF COUNTRY ROCK IN UNDERGROUND EXPLOSIVES MAGAZINES

Foreword

This report attempts to present a survey of the problem of country rock in underground explosives magazines.

It deals first with the importance of this problem within the framework of the safety of such installations as a whole. This is followed by a qualitative presentation of the various factors that influence the problem of country rock. Finally, some of the formulations in use today are discussed and compared. This report does not, however, exhaust the subject, and the same is true of the conclusions derived therefrom.

The specific purpose of this report is to serve as a point of departure for future investigations of this problem.

The report was compiled after the Thun meeting of 9/10 December 1976, of the working group of German, Swedish, Norwegian, and Swiss experts, the group formed to carry out so-called "Operation Block," and which since then has been engaged in a regular exchange of experience in the field of explosives storage.

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1. Introduction

Big explosives magazines frequently are built underground to better control the effects of accidental explosions (Figure 1).

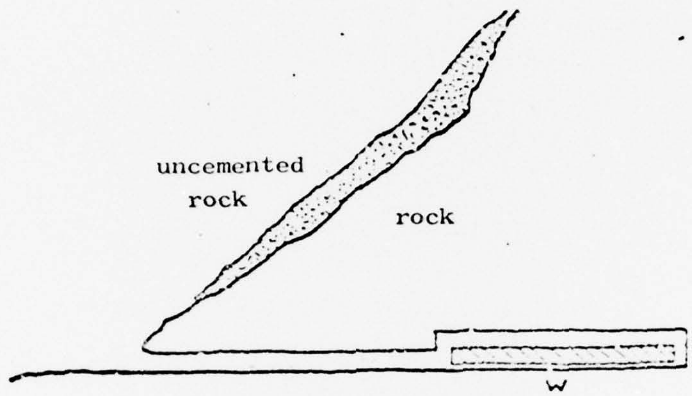


Figure 1. Typical cross section of an underground magazine.

Adequacy of country rock is specified for individual storage chambers, because such adequacy will avoid additional, significant cratering effects in the storage chamber proper, and this is in addition to the explosion effects that escape from the entrance tunnel. The result is a reduction in the total area subject to explosion effects, as compared to those taking place in an above-ground storage area (Figure 2).

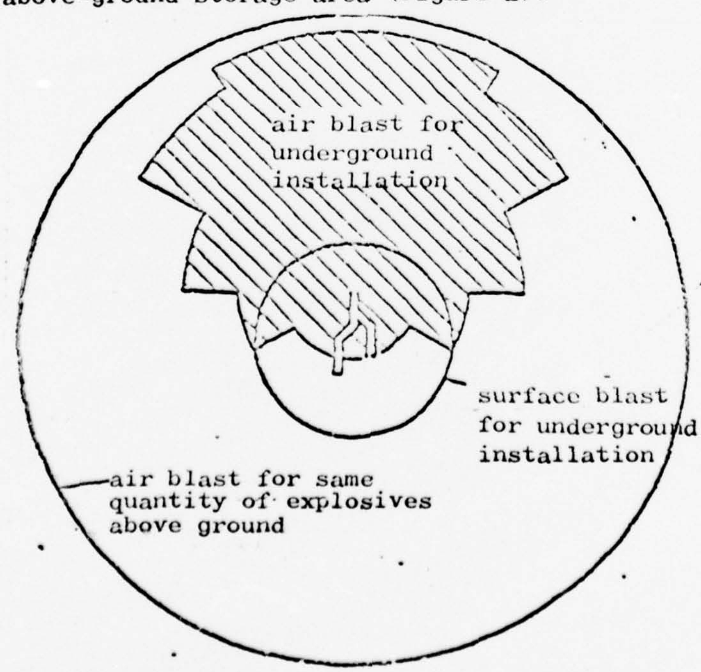


Figure 2. Comparison between danger zones around underground and above-ground magazines.

Adequacy of country rock also is a prerequisite for the effective use of energy dissipators, which too help to reduce the effects escaping from the entrance tunnel (concrete block seal, for example). This can make it possible, in the extreme case, to limit the effects of an explosion on the surrounding area simply to vibration.

Specifications for establishing the country rock criteria, and which are contained in all standards for such installations, therefore are of the utmost importance. A reliable survey of country rock is a prerequisite for the underground storage concept.

However, the result of a comparison of some of the specifications contained in various existing standards is not standard (Figure 3).

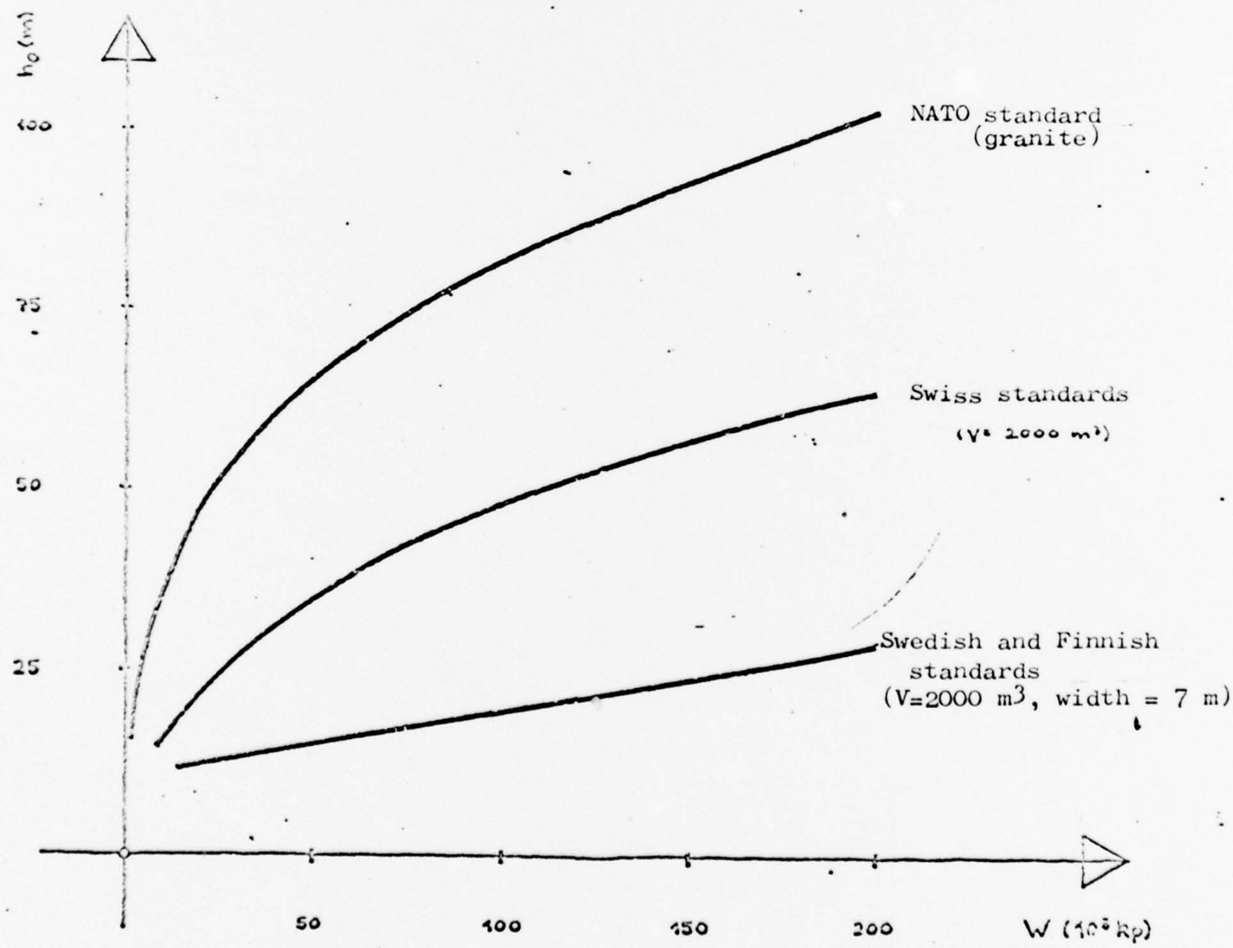


Figure 3. Comparison between various standards for country rock.

Very different results are obtained for the same situation, as will be seen. Moreover, different parameters are contained in the formulas, and tables, under consideration, to wit:

The country rock required in tables of Finnish and Swedish standards is determined as a function of charge density (t/m^3), and chamber span.

Some parameters in the NATO standards, which are used in the FRG and, in principle, in Norway too, are total charge and type of country rock (granite, limestone, sandstone).

The following formula is contained in the Swiss standard currently in effect:

$$W = 2.7 \cdot h_o^{2.25} \cdot V^{0.25}$$

where

W is the charge (kg);
h_o is country rock (m);
V is chamber volume.

The differences between the various standards therefore are not even expressed in the same terms with respect to country rock required. Sometimes one, and sometimes the other, standard can provide higher values, depending on the case.

It certainly is possible to state values for the country rock required for a storage chamber that will have the highest probability of being on the safe side. However, this serves no purpose in many cases. On the one hand, the country rock required determines the length of the entrance tunnel, and as a result influences the economic feasibility and operation of an installation. On the other hand, and what is much more important, is that it often is very difficult to find suitable locations with adequate country rock; the greater the requirements for country rock, the greater this difficulty. Finally, the depth of country rock is stated in terms of existing installations, and this applies to the majority of cases in many countries. In such cases applicable standards determine the possible use of such storage chambers.

Reliable data and knowledge concerning the problem of country rock therefore are of great interest.

Despite the great significance of this problem, why all the great uncertainties that still exist? This question is raised in particular because of the quite extensive research that is going on today in the field of crater formation.

One of the main reasons probably is that there are a number of significant differences between the elementary, and thoroughly studied basic problem of crater formation, and the problem we are dealing with (Figure 4).

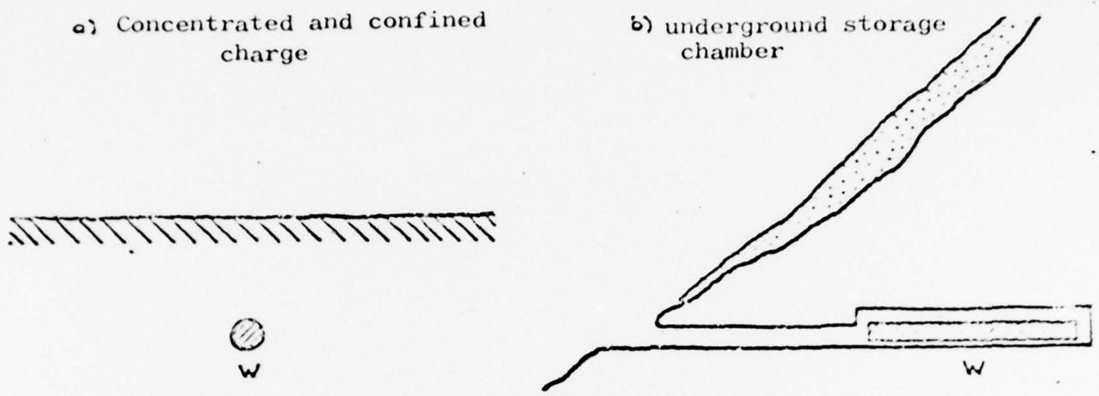


Figure 4. Comparison between the basic case of a buried charge and an underground storage chamber.

It is extremely difficult to derive the necessary principles experimentally at reasonable cost in the case of an explosives magazine, as compared to the basic case. This difficulty is primarily associated with the great many parameters involved. In addition, knowledge of model laws that apply to model tests are lacking for many aspects of the problem.

The next section will discuss the qualitative differences between cases (a) and (b). Section 3 will deal with some of the quantitative formulations.

2. Major Influences on Country Rock

2.1. Safety criterion

Let us discuss the basic problem of the safety criterion before dealing with the physical questions of country rock.

There can be two limiting cases:

(a) The vibration at ground level must be such that there is no serious danger to persons, buildings, or other installations that may be present.

(b) A limited crater effect is permitted, provided this effect does not subject important objects at the site to unacceptable danger.

Of course, there can be many solutions between the two limiting cases. The establishment of this criterion obviously has great influence on the country rock values required.

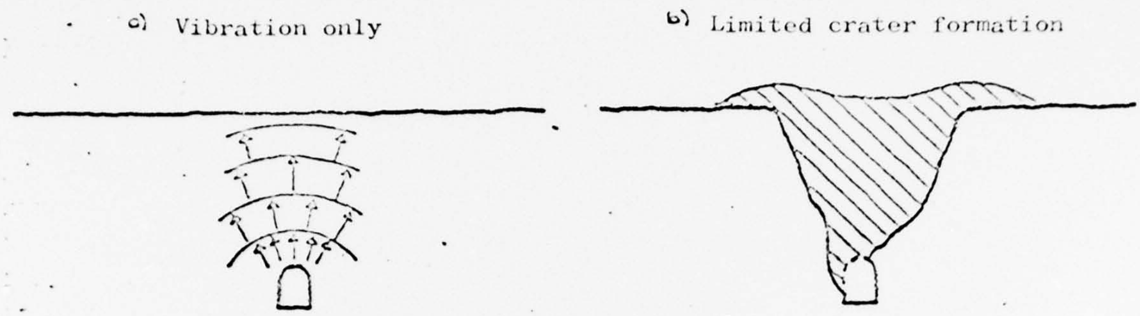


Figure 5. Limiting cases of the country rock criterion.

The standards in question generally do not hint at this problem. The concept of a "squeeze mine" is sometimes mentioned with respect to corresponding principles. This would clearly indicate criteria close to case (b) in Figure 5. Basically, this seems to be logical. However, the main problem is that crater effects are, as is known, widely dispersed, relatively speaking. So we must raise the question of the extent of the "safe distance" from case (b) in order to eliminate undesirable effects with an adequate degree of probability.

The "squeeze mine" criterion is, as it were, a limiting case of crater formation. But a country rock criterion could just as well be defined as a limiting case of vibration effect. Ever greater vibration finally leads to spalling effects, and as a result to loosening of the rock surface. A criterion also could be defined by limiting the spalling depth, spalling rate, etc.

The question, in the concrete case, is where these two types of criteria, the "crater limit criterion" and the "vibration limit criterion" meet, or whether they intersect.

We therefore have a qualitative problem (which criterion?) and a quantitative problem (up to what intensity?) for the country rock criterion.

2.2. Physical limitations

2.2.1 Survey

The following elucidations are based on the basic model of a completely confined, concentrated charge, as shown in Figure 4. Deviations from this basic model will be described as clearly as possible.

The relevant limitations can be divided into four groups:

geometry;

confinement;

grade of rock;

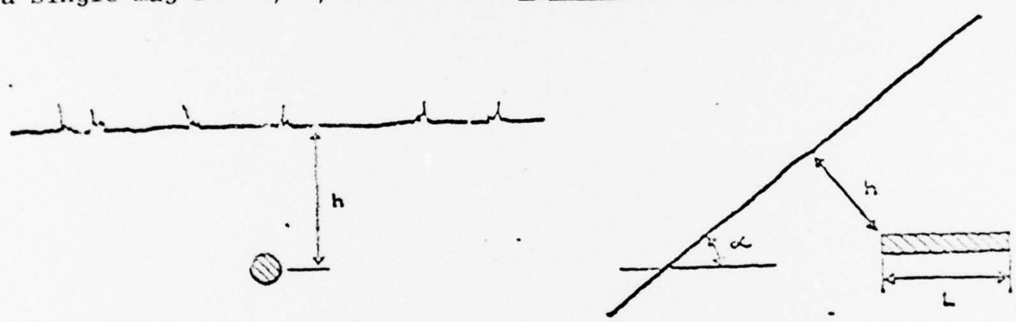
course of the explosion.

These four influences will be discussed in qualitative terms, if briefly, in what follows.

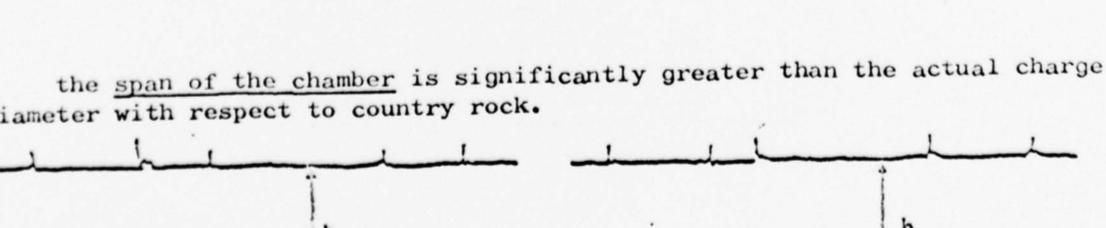
2.2.2 Geometry

Deviations in geometric relationships can be divided into three factors:

the position with respect to the surface can no longer be determined by a single magnitude, h, because the charge is elongated;



terrain configuration usually deviates more or less from a plane;

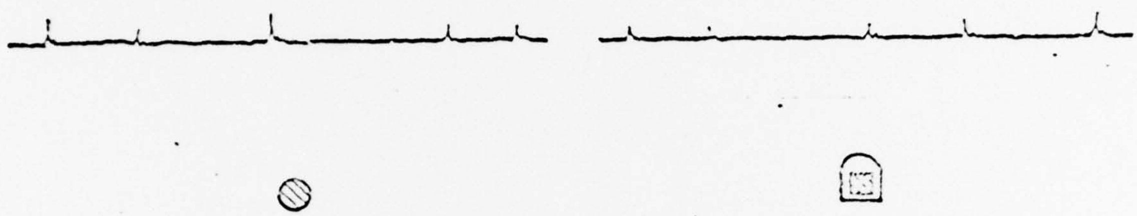


the span of the chamber is significantly greater than the actual charge diameter with respect to country rock.

2.2.3. Confinement

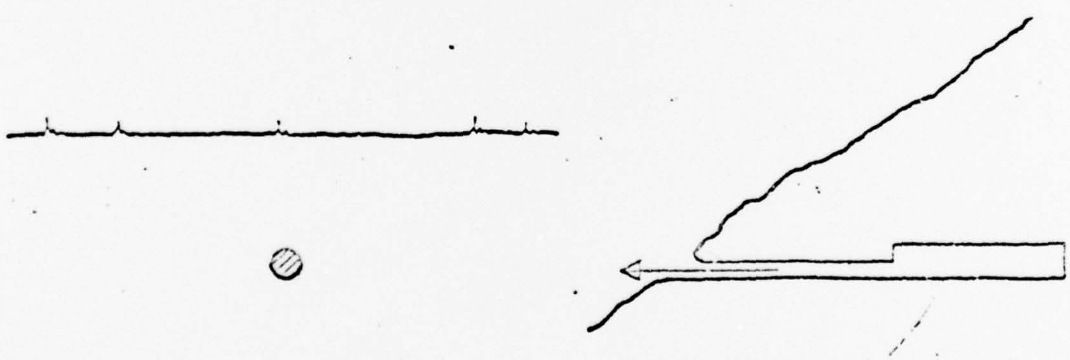
Confinement differs in two respects.

A so-called decoupling effect develops as a result of the cavity around the charge.



$$\bar{\gamma} = \text{density of charge} = \frac{\text{explosive weight}}{\text{chamber volume}}$$

In addition, there usually is a decoupling effect through the entrance tunnel of the storage chamber.



2.2.4. Country rock characteristics

Country rock characteristics naturally influence the effects of a fully confined, concentrated charge, a situation designated in Figure 4 as the basic case. The majority of experiments made with such charges were conducted with significantly smaller quantities of explosives than those present in an explosives magazine. Thus, there should be fewer inhomogeneities within the area of rock influenced by the effects. In addition, it is assumed that homogeneous rock conditions are preferred for tests to the extent possible.

At least three factors play a role in the description of rock conditions:

homogeneous rock characteristics (geological specimen, for example);

rock characteristics within the rock formation (stability, for example), that is, taking regular inhomogeneities (regular, fine cracks, for example) into consideration;

greater inhomogeneities, such as large clefts, change in type of rock (particularly uncememted rock zones).

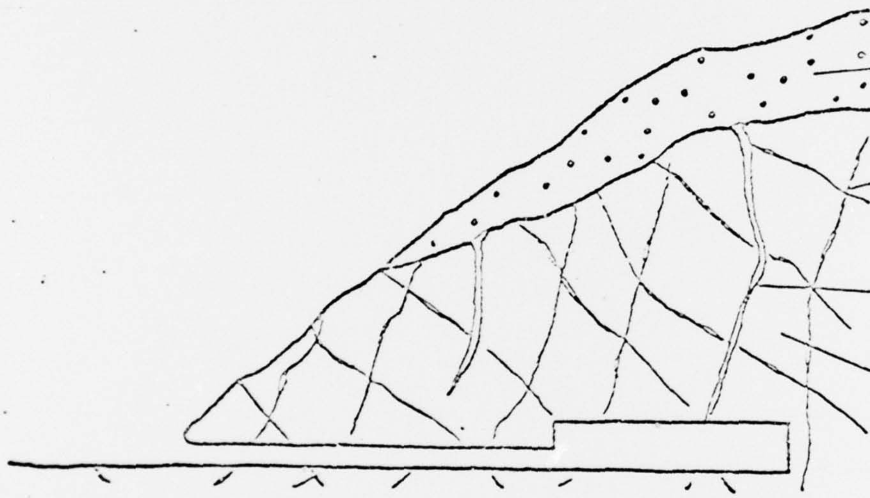


Figure 6. Various effects of rock conditions.

2.2.5. Course of the explosion

This factor must be mentioned here for the sake of completeness. It will not, however, be discussed in what follows.

The explosives stored in the chamber will react like an ideally detonated TNT charge of equal size only in exceptional cases. On the one hand, the decoupling effect through the entrance shaft can be more active because of time delay, and on the other hand, the dynamic shock pressure loads transferred to the rock can be smaller. Although all the material stored may, in the final analysis, participate in an explosion, only part of it should be regarded as being effective for crater effect. There are many cases, in practice, when some part of the material will not take part in the event, but this will depend on the type of material stored.

3. Present Derivations

3.1. Survey

The various of today's models of the crater problem can be grouped into two main categories. The two ways to consider the models, already mentioned in Section 1, are:

the crater criterion as a limiting case of the open crater (squeeze mine);

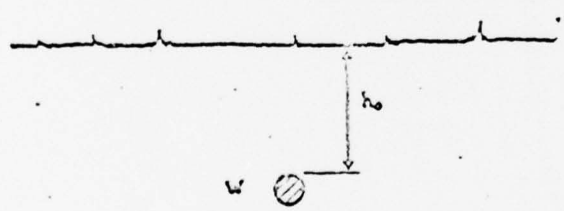
the crater criterion as a limiting case of strong vibration.

A distinction should be made between purely empirical formulas and formulas that attempt to describe a physical process, particularly with respect to the first derivation. Some of the derivations in existence today will be described and discussed briefly in what follows. The influences discussed in Section 2 will be dealt with case by case.

3.2. Derivation of empirical crater formulas

3.2.1. Concentrated and confined charge (grade of rock)

This case is the point of departure for various formulas now in existence and, as already mentioned, is based on extensive experiments with such explosions.



The general formula is as follows, and is based on the laws of similitude:

$$h_0 = \beta \cdot W^{1/3}$$

Magnitudes of β are found in various theorems. But β also depends on the properties of explosives, and on the grade of rock, in the case of fully confined charges. Values of 1.1 to 2.3 are found for β in the literature for a so-called squeeze mine if the formula is standardized such that the explosive factor for TNT is 1. The accuracy with which rock can be graded is limited. Table 1 shows the corresponding references.

Table 1. β VALUES FOR DIFFERENT GRADES OF ROCK ACCORDING TO VARIOUS SOURCES

Dambrun-Ricour [Ref. 1]	light soil	$\beta = 2.3$
	gravel with soil	$\beta = 2.0$
	solid gravel	$\beta = 1.7$
	soft rock	$\beta = 1.4$
	hard rock	$\beta = 1.1$
Present Swiss standard (based on mine formulas by Vauban/Hauser and the evaluation of Castelletto mining enterprises) [Ref. 2, 3]		
	medium rock	$\beta = 1.4$
Ginsburg (evaluation of nuclear tests converted to molecular explosives) [Ref. 4]		
	mean value of all rocks	$\beta = 1.7$
Various other authors without giving grade of rock [Ref. 2]		
		$\beta = 1.15\text{-}1.6$

It would appear that a value of approximately 1.4 is logical for β for medium grade rock. As far as the effects of a squeeze mine are concerned, reference usually is made to the fact that there is no significant ejection of material onto the surface.

3.2.2. Decoupling

The Swiss standards in effect today are based on the empirical derivation for the concentrated, confined charge in the previous section, but they also take the decoupling effect into consideration.

The reduction factor in question was determined in clay and lead in model tests, and found to be [2]:

$$W = \beta^* \cdot f_d^* \; h_o^3 \; ; \quad f_d^* = 10 \cdot \left(\frac{W}{V}\right)^{-1/3} = 10 \cdot \bar{\gamma}^{-1/3}$$

or

$$h_o = \beta \cdot f_d \cdot W^{1/3}; \quad f_d = 0.465 \cdot \bar{\gamma}^{1/9}$$

where

W is the charge in kg;

h_o is the country rock required for a squeeze mine, in m;

V is chamber volume blasted out, in m^3;

$\bar{\gamma}$ is density of charge, in kp/m^3;

f_d is the decoupling factor.

If this factor is used, and if the equation is solved for charge W, we obtain the formula already mentioned in Section 1,

$$W = 2.7\, h_o^{2.25} \cdot V^{0.25}$$

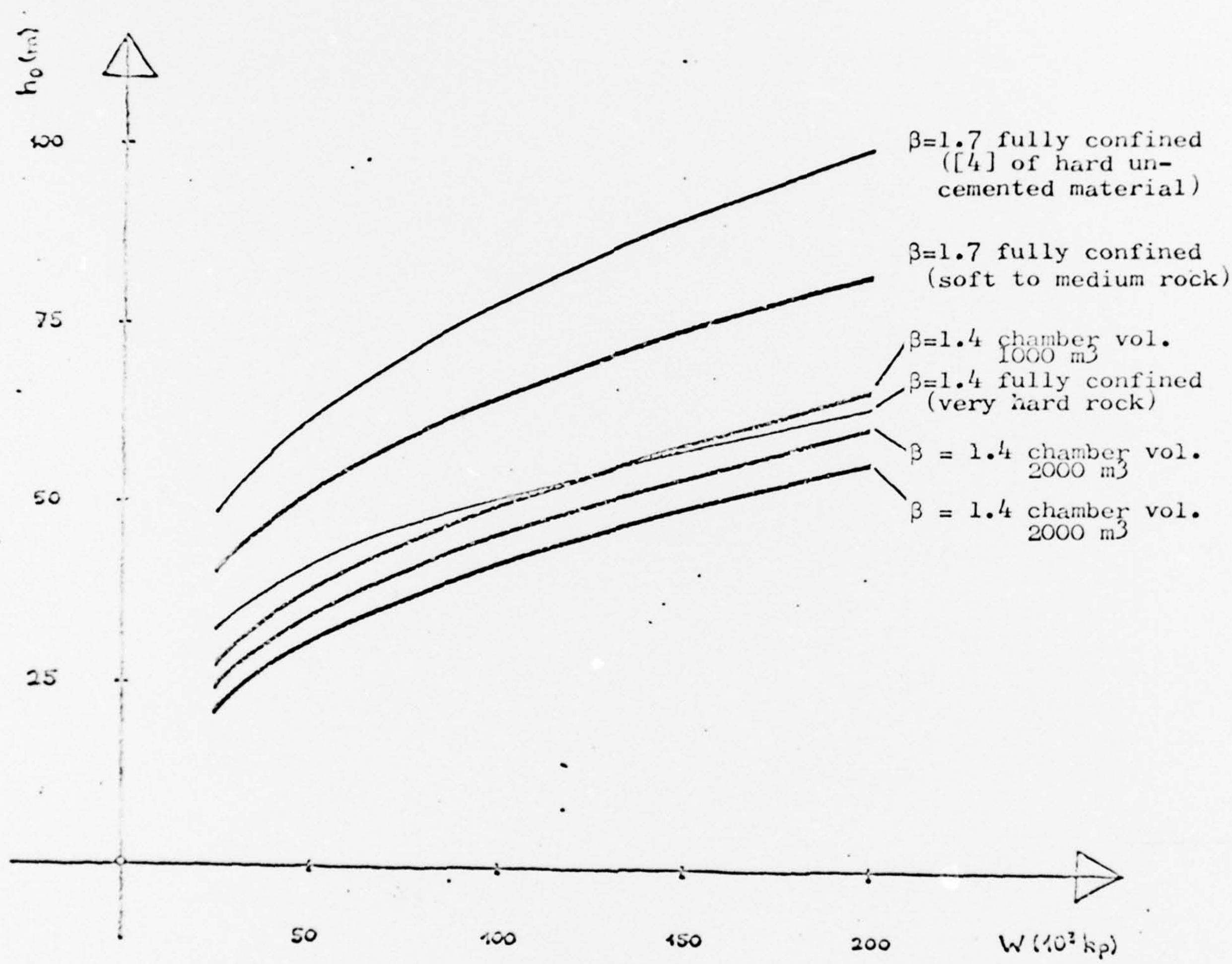


Figure 7. Comparison between required country rock for various rock factors, and between the influence of various chamber volumes, when $\beta = 1.4$.

The above figure shows there is little variation for the chamber volumes in question once decoupling is taken into consideration. On the other hand, the influence of the grade of the rock is significant.

3.2.3. Charge elongation

The KTA (Military Technical Department, now Group of Armament Services of the Federal Military Department), in the early 1960s, proposed a model that takes charge elongation into consideration. This model is based on the following principle [5]:

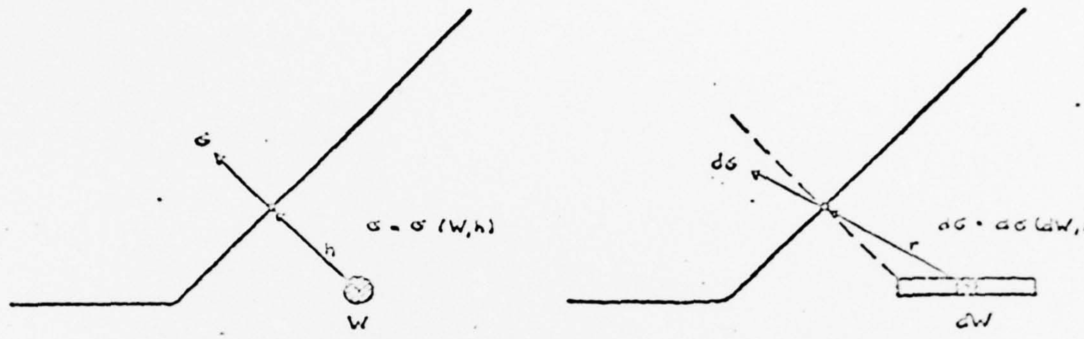


Figure 8. Basic concept of the charge elongation model according to [5].

Each element, dW, of an elongated charge contributes to the stress vector at the critical point on the surface. The critical magnitude of the stress vector was standardized using the case of a concentrated charge. The entire vector field, and not only the stress vector at a single point, was determined using this method, so we can make a statement for a non-uniform terrain (see example in Figure 9).

Figure 10 shows that decoupling and elongation have approximately the same effect in these models. In combination, they result in a great reduction in the country rock required.

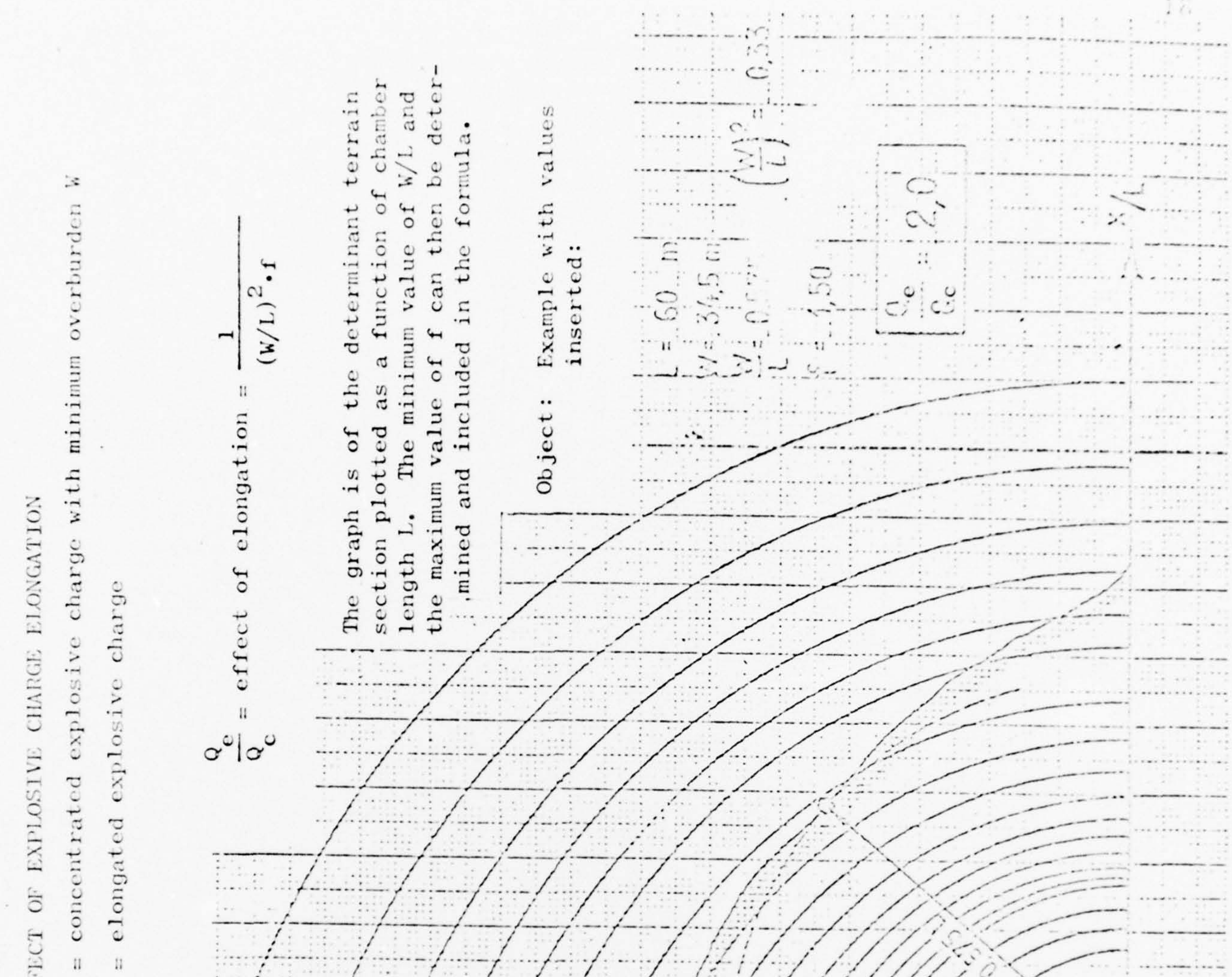


Figure 9. Effect of explosive charge elongation.

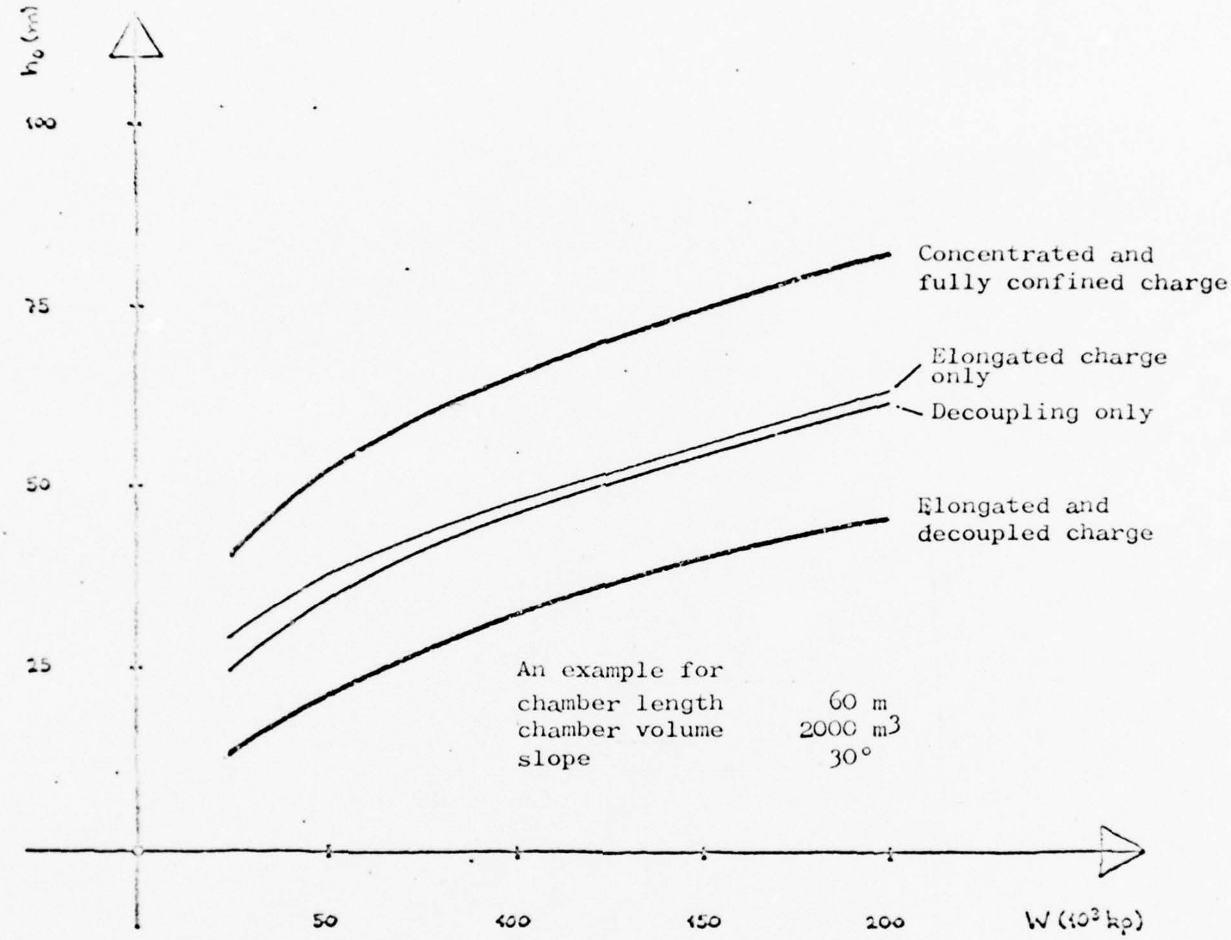


Figure 10. Influence of decoupling and charge elongation according to [2] and [5], respectively.

3.3. Derivation of the formation of caves, or chimneys, during underground explosions

3.3.1. Concentrated and confined charge (grade of rock)

Reference [4] approaches the problem of country rock by using the formation of caves, or chimneys, resulting from an underground explosion. The point of departure is the following premise.

"The course of a confined explosion can be described briefly as follows. The formation of detonation gases produces such great pressure that the original zero space expands to radius R. The cave formed by the pressure of the overlying masses of rock, which are already partially fragmented by the detonation energy, caves in within seconds or minutes. Subsequently, additional masses of rock detach themselves vertically above the explosion center and a vertical chimney is formed. The chimney will not reach the surface if the explosion is completely confined. There will be a subsidence of the ground when the explosion is almost completely confined, and the chimney reaches the surface."

The formulas in question were derived from very simple physical formulations and by evaluating numerous experiments. Here again, the considerations are based on experience with nuclear charges, and a corresponding conversion to chemical charges has been made. Values for various media are given here, as compared to the formula by the same author mentioned in Section 3.2.1.

The formula for finding the necessary overburden is obtained by equating cave volume to chimney volume. The chimney height then can be found and equated to country rock in the limiting case.

Thus, the relation for country rock required is

$$h_o = \frac{(K \cdot C)^{0.8}}{\rho^{0.2}} \qquad W_{[t]}^{4/15}$$

The values of K, C, and ρ will depend on the rock and are given in [4].

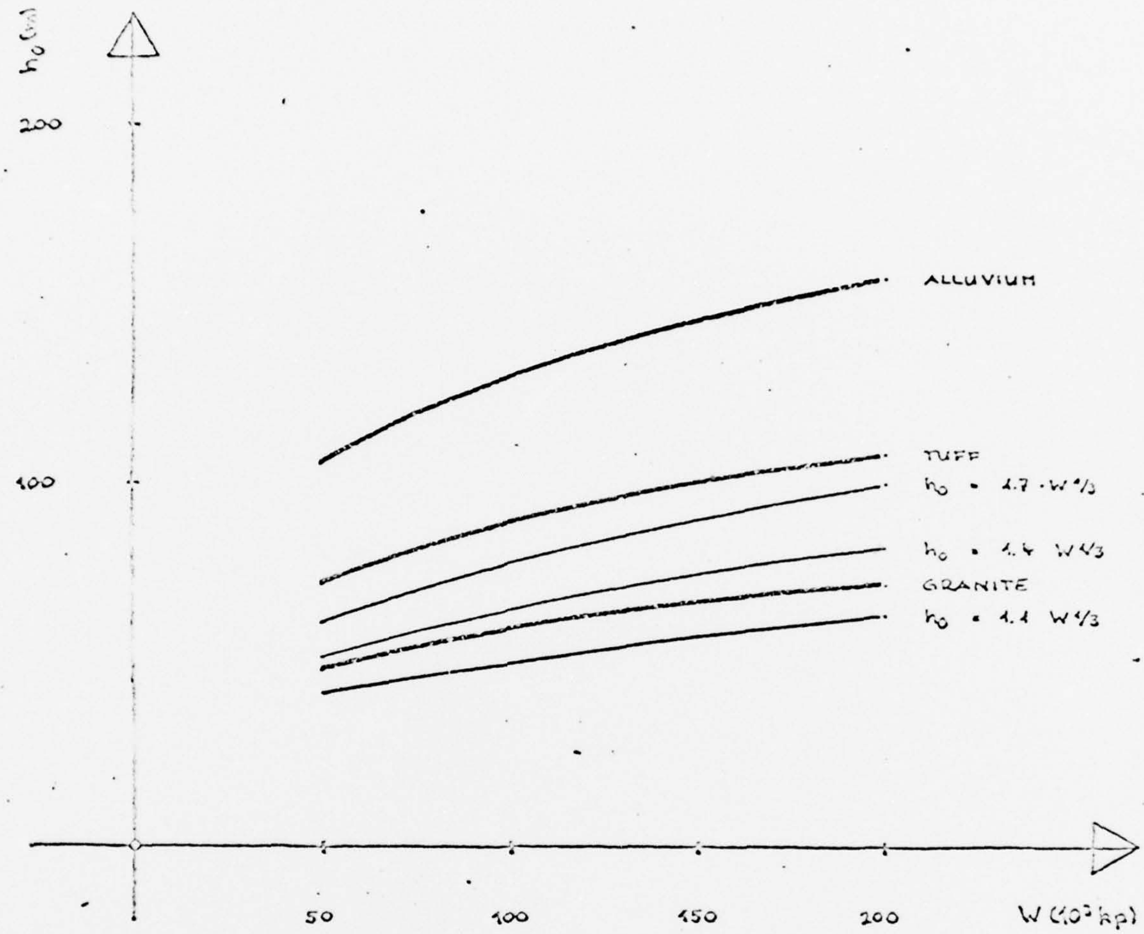


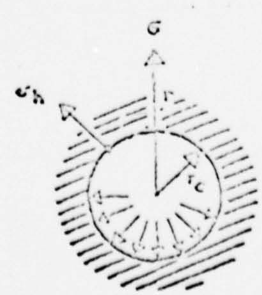
Figure 11. Country rock required according to [4] with chimney model; comparison with empirical crater formulas of Section 3.2.1.

3.3.2. Decoupling

The model of cave formation under discussion here is intimately associated with the problem of stress propagation, so let us briefly derive the decoupling effect that is based on stress propagation. Section 3.4.1 will discuss this derivation in detail.

Based on the relationship

$$(r) = {}_h(r_c / r)$$



the ratio of the equivalent, fully coupled charge, W*, to the effective charge, W, can be stated as follows

$$\frac{W^*}{W} = \left(\frac{\bar{\gamma}}{\gamma_s}\right)^{\frac{3\kappa - \lambda}{\lambda}}$$

where

k is the specific heat ratio;
λ is the propagation factor.

This derivation matches exactly the decoupling factor given in 3.2.2, and as presently contained in the Swiss standard (when $\gamma_{TNT}^{1/3} = 10$) when $k = 1.2$ and $\lambda = 2.7$ (that is, soft rock).

Thus, the decoupling effect is the same as that mentioned in Section 3.2.2. In contrast to the empirical derivation in Section 3.2.2, the above formula adds two additional magnitudes; k, which differs with density of charge, and the rock factor λ. As already mentioned, this factor will be discussed later.

3.3.3. Charge elongation

The formation of caves, or chimneys, is derived in reference [4] primarily for use in developing an elongated charge model.

We will not discuss the model in detail. In principle, the elongated charge is separated into individual partial concentrated charges, the chimneys of which just touch each other.

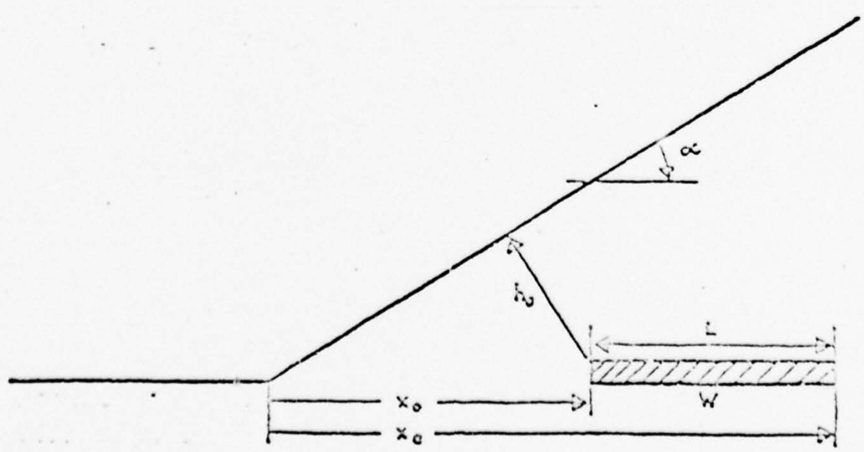


Figure 12. Elongated charge with respect to slope inclinced by an angle α.

The derivation results in the following formula for maximum charge:

$$W = 0.05 \cdot \sin\alpha^{9/4} \quad [x_e^{13/4} - x_o^{13/4}]$$

and when $\alpha = 30°$,

$$W = 0.0105 \quad [(L+2h_o)^{13/4} - 2h_o^{13/4}]$$

Figure 13 compares a concentrated charge with the derivation in accordance with 3.2.3.

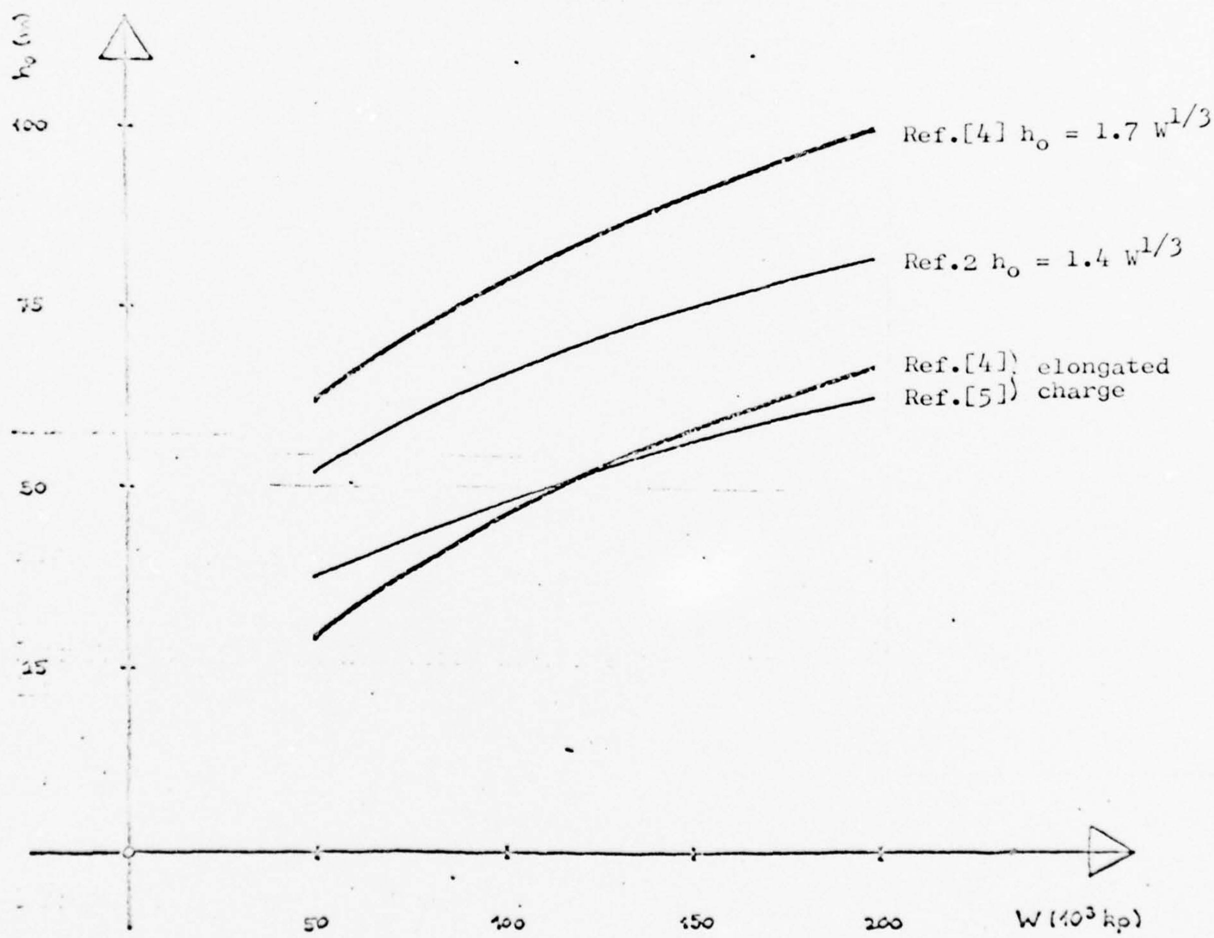


Figure 13. Comparison between concentrated and elongated charge according to references [4] and [2], and [5].

The elongation effect is greater, according to [4]. However, that reference uses more conservative values for rock characteristics, so the final results for country rock values are very close to those cited in [5].

3.4. Derivation of stress propagation laws

Derivations of this type have not been used to date in connection with the problem of crater formation using fully confined loads, so we will deal directly with the problem of the decoupled charge.

3.4.1. Concentrated decoupled charge (grade of rock)

Three zones can be differentiated (Figure 14) when we look at the propagation of pressure, or stress, during an explosion in a rock cavity. The explosion pressure wave propagates in the air in the first zone, the cavity between charge and rock. The stability of the rock in the first zone of the country rock is exceeded when densities of charge are high. The pressure wave propagates elastically into the area beyond the destruction zone that is in the surrounding area (seismic zone).

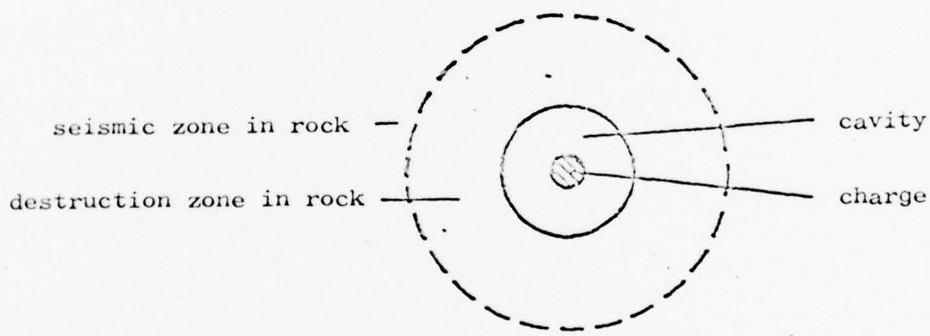


Figure 14. Decoupled explosion pressure propagation into various zones.

Reference [6] presents the appropriate laws of propagation, and the corresponding rock factors are determined in tests using three types of rock. It was found that sufficiently accurate calculations could be made for both rock zones, using one propagation law for those densities of charge of primary interest.

Pressure p_c in the cavity is first determined as

$$p_c = p_{ch} \cdot (r_c/r_{ch})^{-3k}$$

or

$$p_c = p_{ch} \cdot (\bar{\gamma}/\gamma_s)^k$$

Starting with the assumption that radial stress σ_c at the rock wall is proportional to pressure p_c, that is, that

$$\sigma_c = k \cdot p_c ,$$

the following applies for further propagation

$$\sigma(r) = k \cdot p_{ch} \cdot \left(\frac{\overline{\gamma}}{\gamma_s}\right)^{\kappa} \cdot (r/r_c)^{-\lambda}$$

The decoupling effect then can be found by equating the stress of a fully confined charge, W*, to a decoupled charge, W, at the same distance.

fully confined $\quad \sigma^*(r) = k \cdot p_{ch}(r/r_{ch})^{-\lambda}$

$$\text{with } r_{ch} = \left(\frac{3W^*}{4\pi\gamma_s}\right)^{1/3}$$

$$\sigma^*(r) = k \cdot p_{ch} \cdot r^{-\lambda} \cdot \left(\frac{3W^*}{4\pi\gamma_s}\right)^{\lambda/3}$$

decoupled $\quad \sigma(r) = k \cdot p_{ch}\left(\frac{\overline{\gamma}}{\gamma_s}\right)^{\kappa}(r/r_c)^{-\lambda}$

$$\text{with } r_c = \left(\frac{3W}{4\pi\overline{\gamma}}\right)^{1/3}$$

$$\sigma(r) = k \cdot p_{ch}\left(\frac{\overline{\gamma}}{\gamma_s}\right)^{\kappa} r^{-\lambda} \cdot \left(\frac{3W}{4\pi\overline{\gamma}}\right)^{\lambda/3}$$

$\sigma(r) = \sigma^*(r)$:

$$\left(\frac{\overline{\gamma}}{\gamma_s}\right)^{\kappa} \cdot \left(\frac{W}{\overline{\gamma}}\right)^{\lambda/3} = \left(\frac{W^*}{\gamma_s}\right)^{\lambda/3}$$

$$\frac{W^*}{W} = \left(\frac{\overline{\gamma}}{\gamma_s}\right)^{\frac{3\kappa-\lambda}{\lambda}}$$

This also is the decoupling factor for the charge, as already mentioned in Section 3.3.2. Section 3.3.2 showed that this factor corresponds to the decoupling factor derived empirically, contained in the present Swiss standards, when $k = 1.2$ and $\lambda = 2.7$.

As mentioned, reference [6] examined this law for three kinds of rock; Lithonia granite, Bucyrus limestone, and Marion limestone. Here too the calculations were made for $k = 1.2$. The λ values for these three types of rock were found to be

Lithonia granite	$\lambda = 1.9$
Bucyrus limestone	$\lambda = 2.1$
Marion limestone	$\lambda = 2.65$

The last of the three has λ of about 2.7, as was mentioned above. The decoupling effect is even stronger for harder rock. Person cites λ values of 1.5 in [7]. Newmark, on the other hand, cites exponents of $\lambda = 2.5$ in his approximation formulas. However, these refer primarily to more solid, uncemented types of rock [8].

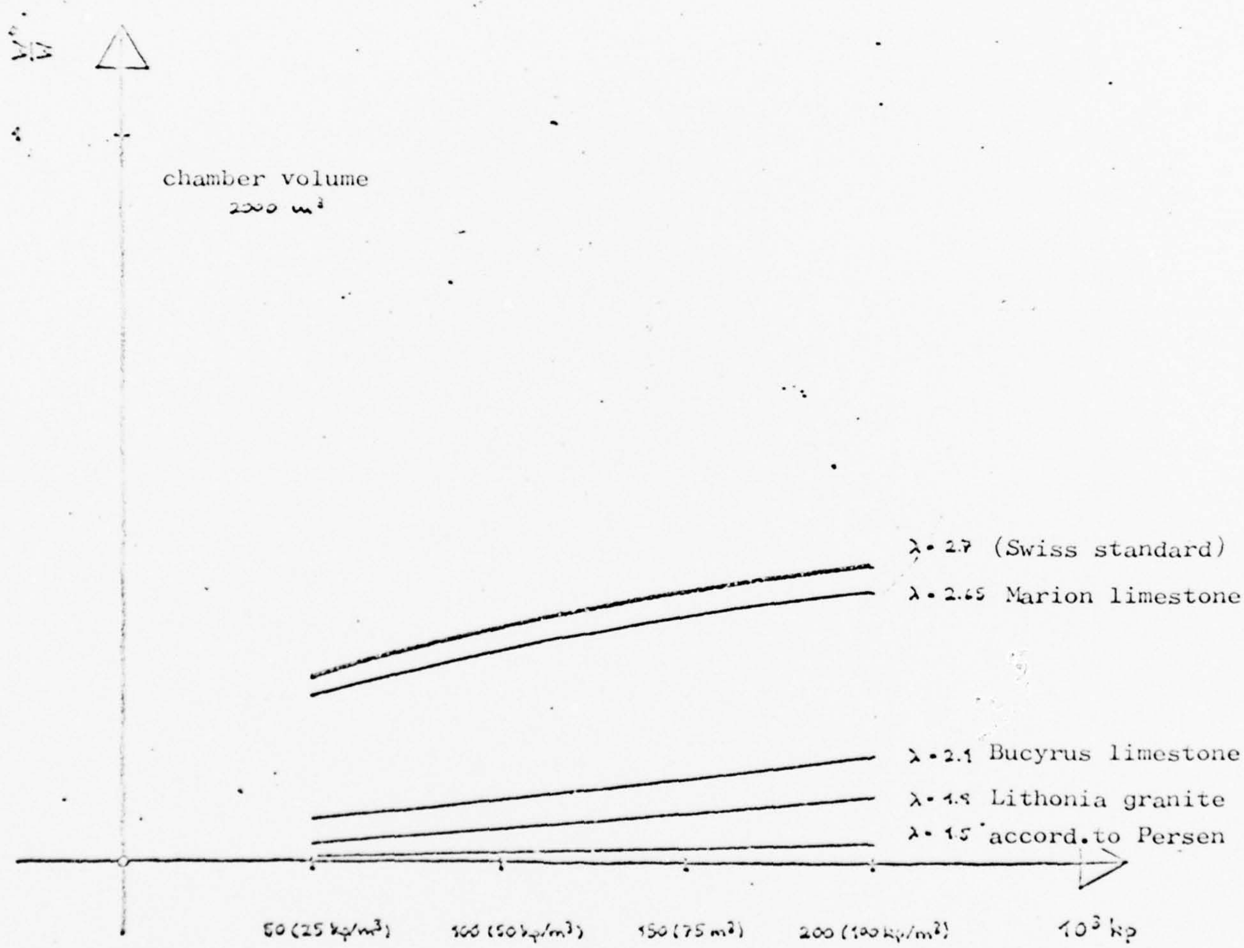


Figure 15. Relationship between fully coupled charge W*, and effective charge, W, for various types of rock according to [6].

According to this derivation, and given corresponding grade of rock, the decoupling effect has such small values that these considerations appear to be quite insignificant, at least as far as the problem under discussion here is concerned. The basic lack of stress propagation derivations will be discussed in brief later on.

3.4.2. Charge elongation

Theoretical treatment of the case, albeit simplified, of an elongated charge is possible by applying the stress propagation law.

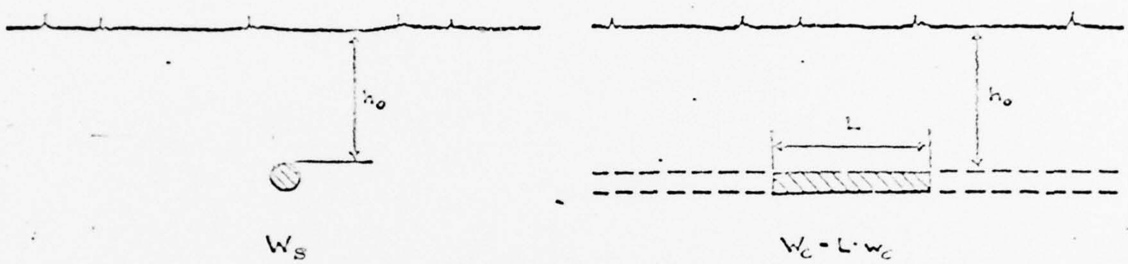


Figure 16. Comparison between spherical charge and equivalent cylindrical charge of length L.

A concentrated charge, W_s, is compared with a cylindrical charge, W_c. Stress propagation is determined in a simplified manner as for a very long charge. The model therefore is reliable, the more so because the rock surrounding the cylindrical charge is taken as constant.

The considerations, primarily supported by references [6] and [9], are based on the following relationships:

stress for spherical charge $\sigma_s(h) = K(h/r_s)^{-\lambda_s}$

stress for cylindrical charge $\sigma_c(h) = K(h/r_c)^{-\lambda_c}$

where

K is a constant that depends on the detonation pressure of the explosive;

r_s, r_c are the radii of the spherical and cylindrical charges, respectively;

λ_s, λ_c are the propagation factors for the spherical and cylindrical cases, respectively.

It can be shown that a propagation factor of $\lambda_s = 2.7$, as used in Section 3.4.1, corresponds to $\lambda_c = 1.9$ for cylindrical wave propagation (reference [9]).

The following substitutions are made in the above formulas:

$$r_s = \left(\frac{3\,W_s}{4\,\pi\,\gamma_s}\right)^{1/3}$$

$$r_c = \left(\frac{W_c}{L\,\pi\,\gamma_s}\right)^{1/3}$$

and the dimensional condition for the squeeze mine in the case of a concentrated charge is introduced

$$h_o = 1.4\,W_s^{1/3} \qquad \text{(in m and kg)}$$

Then setting $\sigma_s(h_o) = \sigma_c(h_o)$, we obtain

$$W_c \equiv L \cdot W_s^{2/3} \qquad \text{(in m and kg)}$$

This relation is evaluated for various chamber lengths, L, in Figure 17. The reductions for elongation are smaller than in the other derivations because of the already mentioned simplifications. The result is a reduction in the permissible charge for small chamber lengths, which, naturally, is unrealistic and stems from the simplifcations. At any rate, what is shown is that significant reductions in country rock requirements are possible for a chamber length of 100 m, despite the conservative simplifications.

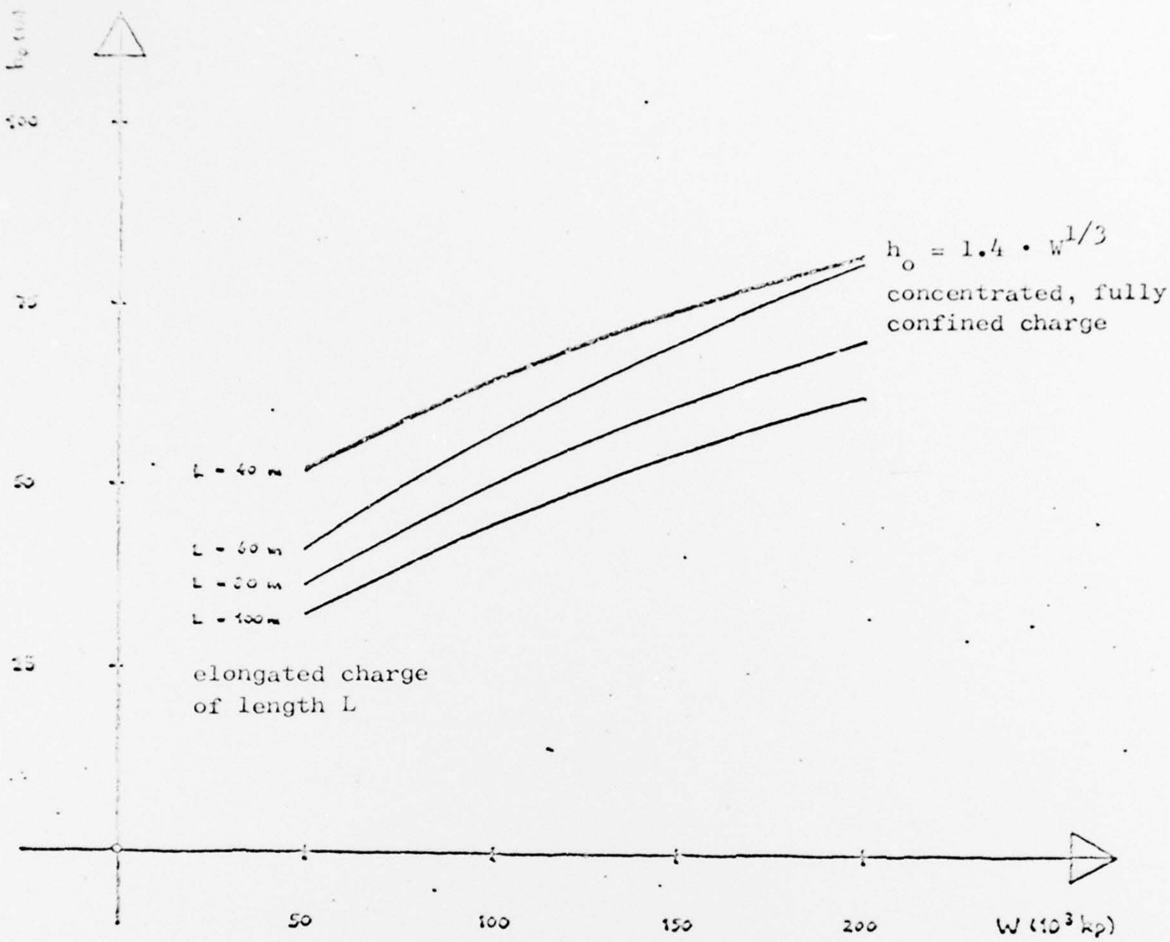


Figure 17. Country rock required for a cylindrical charge of length L parallel to the surface.

The model used here would be in relatively good agreement with the case shown in Figure 18.

Figure 18. Magazine chamber with more or less uniform country rock.

3.4.3. Critical remarks concerning the derivation of stress propagation

The derivation of stress propagation unquestionably is applicable in cases where relatively high requirements are imposed for the country rock criterion, so it is correct, in principle, when we are dealing with an evaluation of vibration, but when no relevant destruction phenomena, which tend in the direction of actual crater formation, develop in the surrounding material.

However, the correctness of the conclusions drawn from these derivations must be looked at with a critical eye because the tendency to apply broad-based criteria such as these should be avoided.

As already mentioned, vibration effects are certain to be the first, but weakest, effects to appear on the surface in the event of underground explosions. These effects increase with increase in charge, and the final result of further increase is increasingly marked crater formation.

Two simple examples (Figure 19) will demonstrate that two completely different mechanisms can be at work here, mechanisms that have little connection with each other.

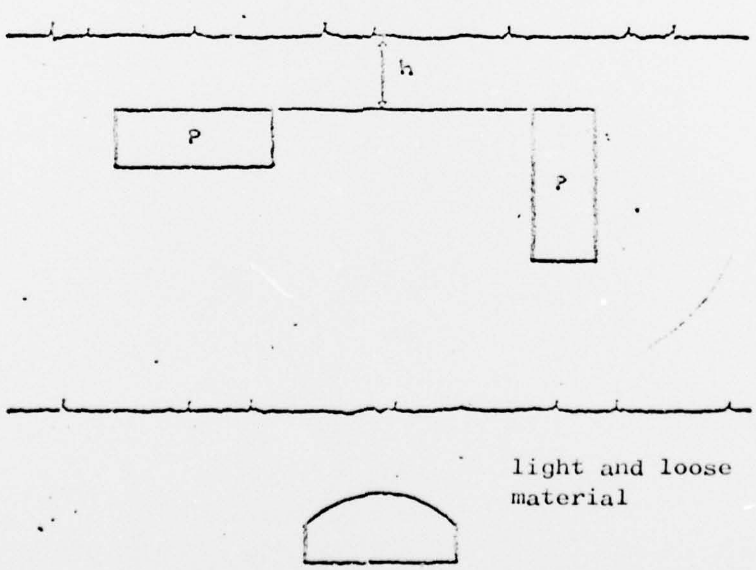


Figure 19. Examples of the questionable application of the stress propagation derivation.

Example 1 is presented to show that maximum stress at the surface can everywhere be approximately equal, depending on the geometry, but that

total force acting on the country rock can, at the same time, be considerably different.

Example 2 shows, for example, that light and loose overburden tends to reduce stress rather well, but that at the same time the corresponding resistance of the overburden is very low.

Based on these considerations, the derivations in this section were not used to derive actual country rock formulas, but only to find derivations for the "decoupling" and "elongation" reduction factors.

We should comment on the problem of an elongated charge in the inclined surface case (Figure 20).

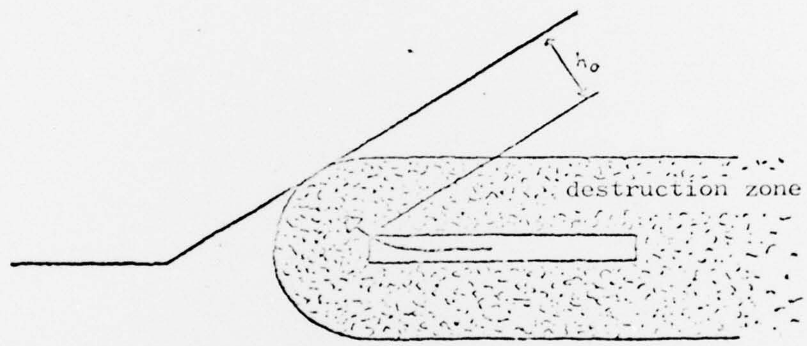


Figure 20. Aftershock created by explosion gases from an elongated charge at the site where country rock is weakest.

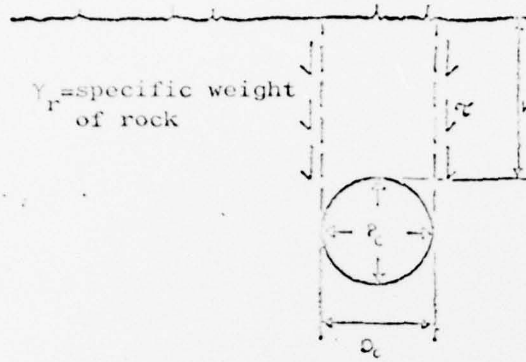
We must ask ourselves if, in this situation, the total charge influences the crater effect, despite elongation. The country rock can be loosened at its weakest point, particularly when it is somewhat thin. The question of the extent to which debris will be ejected then can depend on the total volume of explosion gases present at the time of the aftershock.

3.5. Derivation of a simple equilibrium model

This derivation, like that discussed in 3.4, is not concerned with the fully confined charge case, so the decoupled charge is discussed directly.

3.5.1. Concentrated decoupled charge (grade of rock)

The point of departure for this derivation is a very simple equilibrium model that equates explosion gases driving force to country rock resistance (Figure 21).



$$\pi \frac{D_c^2}{4} \cdot p_c = D_c \cdot h \cdot \pi \cdot \tau + \frac{\pi \cdot D_c^2}{4} \cdot h \cdot \gamma_r$$

Figure 21. Simplified equilibrium model.

The fractional model probably is not very realistic. However, the important thing here is to find a derivation that relates all relevant parameters.

Chamber pressure, p, is derived in accordance with reference [6] as

$$p_c = p_{ch}(r_c / r_{ch})^{-3k} = p_{ch}\left(\frac{\overline{\gamma}}{\gamma_s}\right)^{k}$$

Setting $p_{ch} = 10^6$ psi and $k = 1.2$ according to [6], we obtain the following approximation formula for chamber pressure

$$p_c \, [kp/m^2] = 10^5 \cdot \overline{\gamma}^{-1.2}_{[kp/m^2]}$$

This formula will not be compared with other approximation formulas for chamber pressure, but the same bases will be used, wherever possible, in order to compare it with the derivations presented in the preceding sections.

The relationship for required country rock then can be written as

$$h_o = \frac{10^5 \cdot \overline{\gamma}^{1.2} \cdot D_c}{4\tau + D_c \cdot \gamma_r} \qquad (m, kp)$$

Note that that part of the surrounding weight in the area that is relevant in practice is negligible. Then

$$h_o = 0.25 \cdot 10^5 \frac{\overline{\gamma}^{1.2}}{\tau} \cdot D_c \qquad (m, kp)$$

The characteristic magnitude for rock resistance, τ, is determined by comparison with the formula in the Swiss standards. However, note that the value becomes dependent on density of charge, that is, the models differ with respect to the influence of density of charge [τ (kp/cm^2) = 4.8 $\gamma^{-0.76}$ (kp/m^3)].

Figure 22 shows that the decoupling effect is greater for smaller charges than previously presented derivations yield if the formula is standardized for a density of charge of 100 km/m^3 (that is, τ = 160 kp/cm^2). Correspondingly greater overburden is necessary for high densities of charge if standardization is on a density of charge of 25 kp/m^3 (that is, τ = 53 kp/cm^2).

Actually, magnitude τ would be suitable for use in taking rock characteristics into consideration. However, because it is directly proportionate to overburden height, h_o, it is much more variable than the rock factor, β, introduced in 3.2.1, which varies only by a factor of approximately 2 between loose rock and hard rock. There is, therefore, a significant contradiction between this derivation and the empirical formulas.

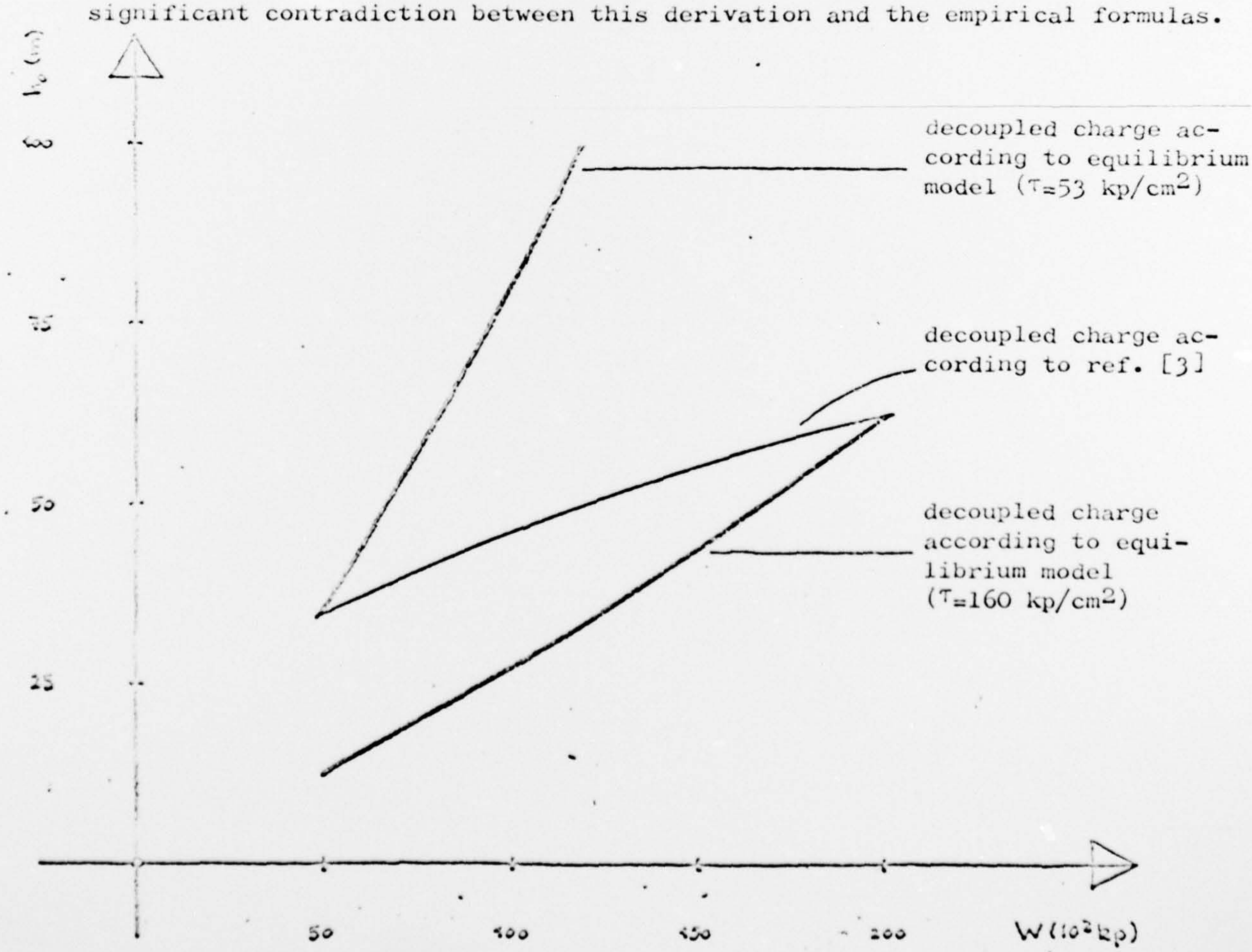


Figure 22. Decoupling effect according to equilibrium model and Swiss standard [3].

3.5.2. Charge elongation

The basic model permits a relatively simple transition to be made to an elongated charge. A chamber parallel to the surface is assumed, as in 3.4.2. However, the effect of the limited length of the charge can be fully taken into consideration in this case. Here again, the decoupling effect is not included simultaneously.

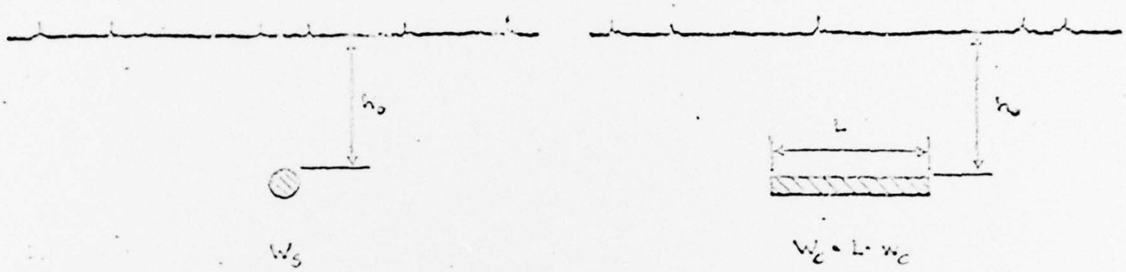


Figure 23. Comparison between spherical charge and equivalent cylindrical charge of length L.

The equations for the overburden, h_o, are derived for a sphere, and for a cylinder, as follows:

sphere
$$h_{o_s} = \frac{1}{2} \frac{p_{ch}}{\tau} \cdot \left(\frac{3 W_s}{4 \pi \gamma_s}\right)^{1/3}$$

cylinder (simplified, without resistance of broad dimension)
$$h_{oc} = \frac{p_{ch}}{\tau} \cdot \left(\frac{W_c}{L \pi \gamma_s}\right)^{1/2}$$

The following approximation formula is obtained from $h_{os} = h_{oc}$

$$W_s = 0.16 \cdot \left(\frac{W_c}{L}\right)^{3/2} = 0.16\ W_c^{3/2} \qquad \text{(m, kp)}$$

Disregarding the broad dimension of the cylinder, which makes no relevant contribution to resistance, means that the cylinder can be regarded as infinitely long. Thus, the above equation provides a concentrated charge, W_s, equivalent to a linear load, w_c, parallel to the surface.

Figure 24 evaluates this formula. It shows a very strong reduction effect for the required overburden.

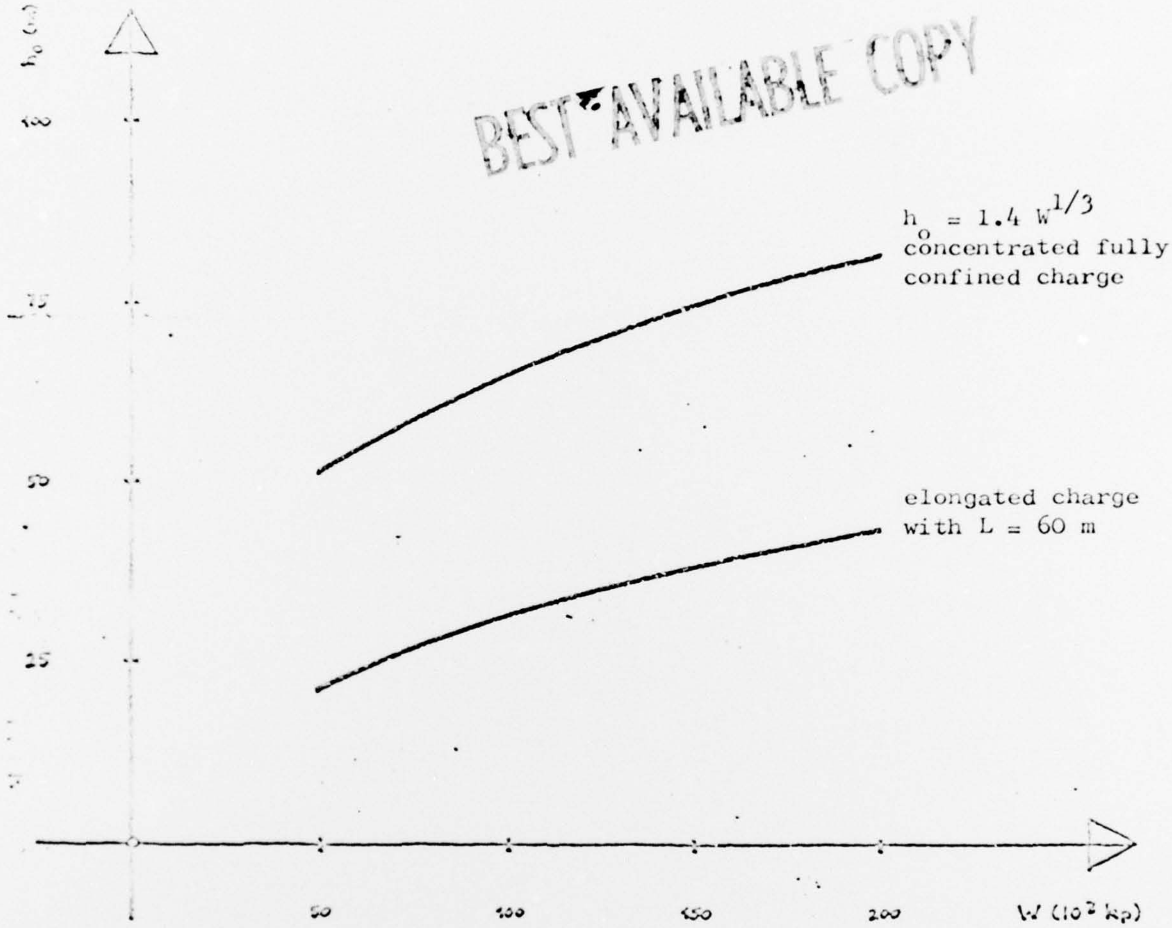


Figure 24. Elongation effect for a cylindrical charge parallel to the surface according to the equilibrium model.

4. Summary and Conclusions

An elegant summary of all the results presented in the foregoing is extremely difficult. However, the following three figures are an attempt to present an overview.

Figure 25 again shows NATO, Sweden/Finland, and Switzerland standards. Curves for a fully coupled charge (squeeze mine criterion), and the curve for a decoupled and elongated charge according to [5] are plotted as the

reference curves. One major factor seen is that the NATO criterion is the inverse of the squeeze mine criterion, as far as grade of rock is concerned. Thus, the NATO standard would appear to be based primarily on a vibration criterion. Curves for softer rocks, on the other hand, appear to almost coincide with the squeeze mine criterion. Swedish and Finnish standards are below the curve for coupled and elongated charges determined in accordance with reference [5]. Lower values for country rock can be shown in other references, but only for very good grades of rock. Thus, both the top and the bottom curve in Figure 25 could apply to very good grades of rock!

Figure 26 is a compilation of the decoupling effect. Here the dispersion is arbitrarily great, with good grades of rock providing a high decoupling effect. The influence of chamber volume is significantly less than that of grade of rock. As already indicated earlier, the extremely high decouplings for high grades of rock can hardly be realistic with respect to the problem investigated here.

Figure 27 is an analogous survey of the problem of charge elongation. Here, the dispersion is not as great. The fact that even a cylinder parallel to the surface results in a reduction of the country rock required, reinforces the impression that it is certainly justified to give reasonable consideration to the elongation effect.

Not all the influences mentioned in Section 2 were discussed in Section 3, but three of the most important elements, grade of rock, decoupling, and charge elongation were. The question of the extent to which stress propagation models can be used to evaluate these effects is of major significance.

This report is primarily intended to stimulate further discussion. One important question is the damage criteria to use as the basis for country rock requirements.

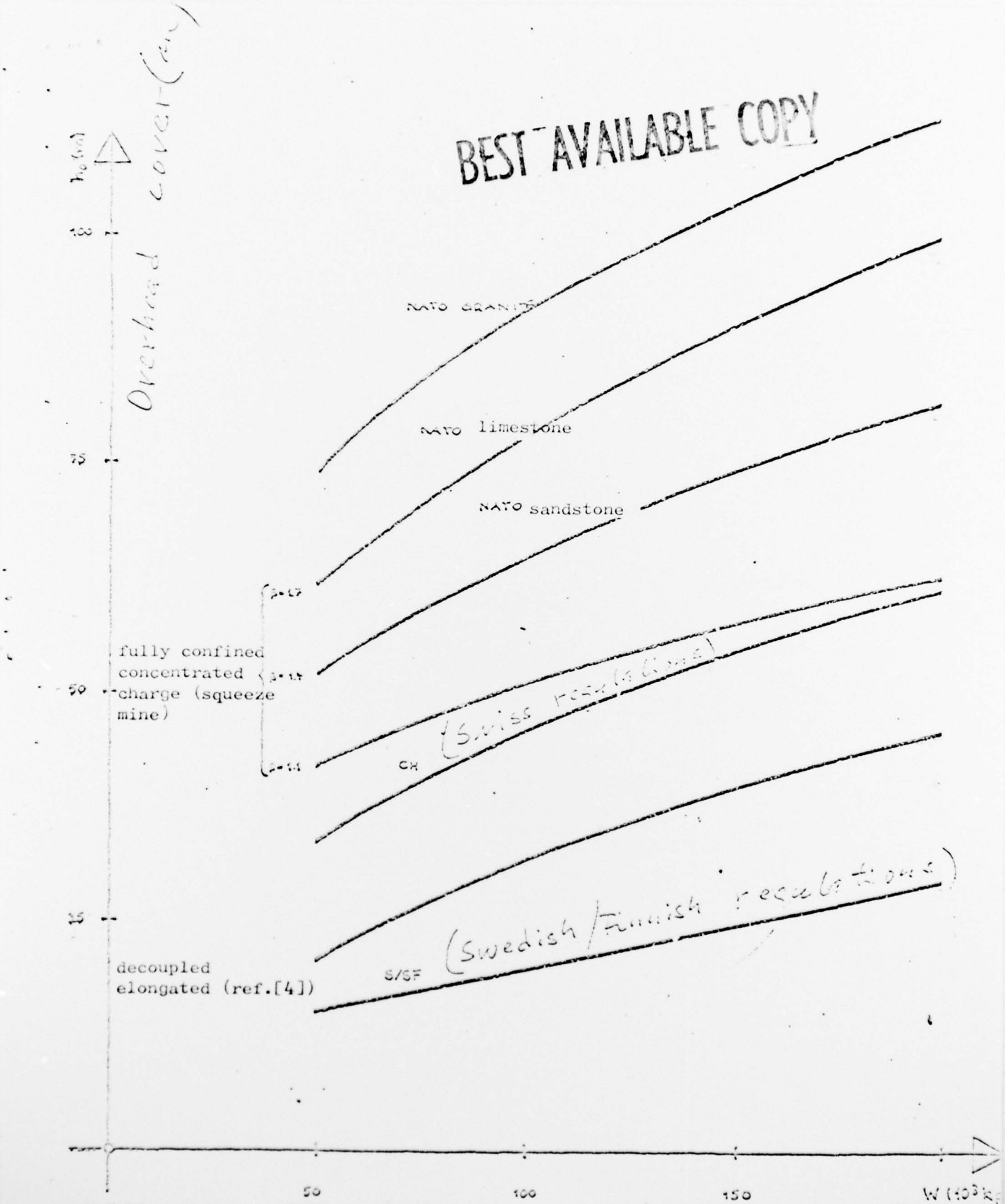


Figure 25. Comparison between the various standards and some of the derivations discussed.

Figure 26. Comparison between decoupling effects according to various derivations.

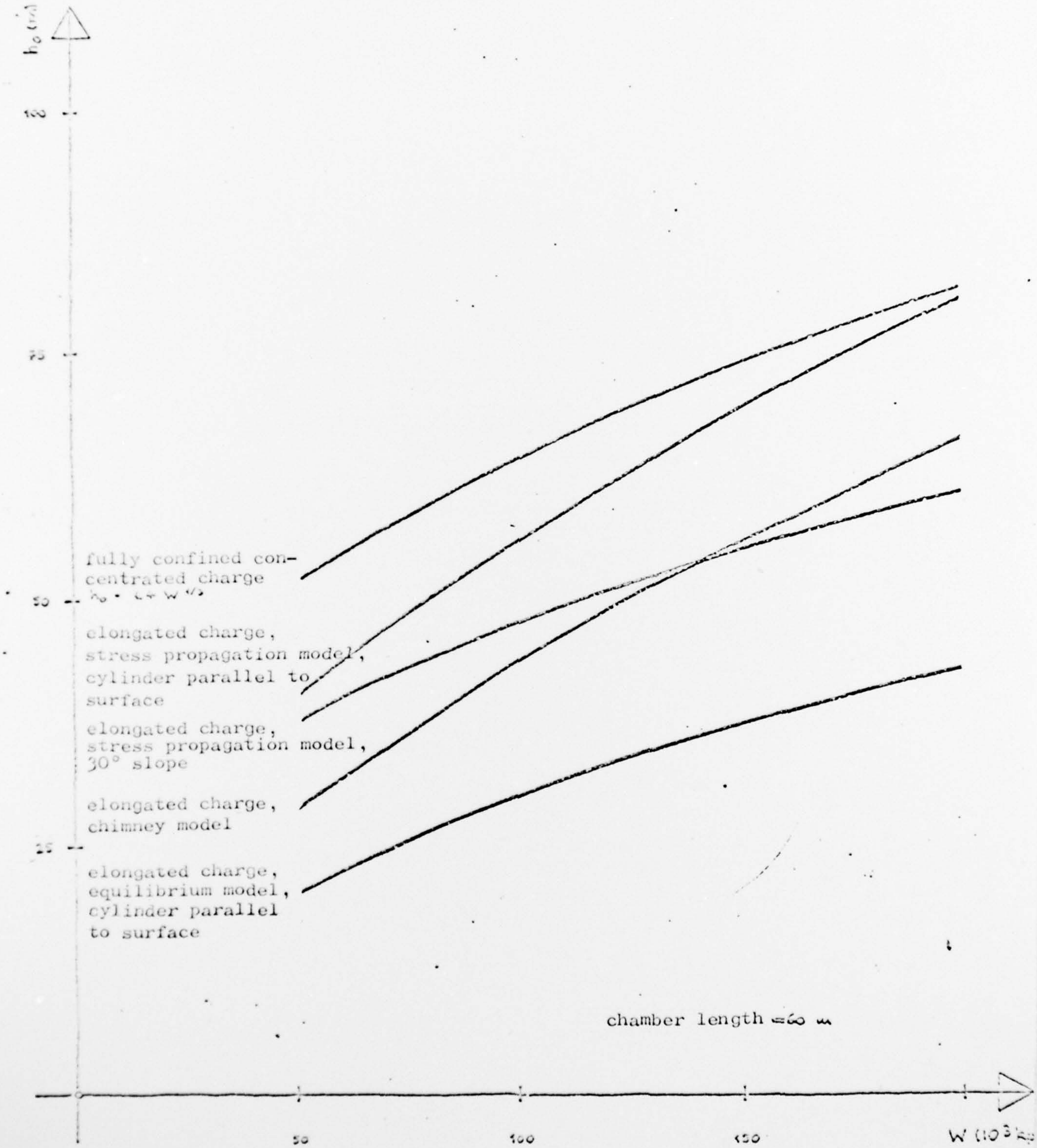


Figure 27. Comparison between charge elongation effects according to various derivations.

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List of Symbols

h	country rock; that is, shortest distance of the charge, or chamber, to rock surface
h_o	country rock required [overburden]
W	effective charge
W^*	equivalent, fully coupled charge
W_s	spherical charge
W_c	cylindrical charge
w_c	weight per linear meter of the elongated, or cylindrical, charge
V	chamber volume
r_c	$\frac{D_c}{2}$ = cavity radius
r_{ch}	charge radius
r_c	cylindrical charge radius
r_s	spherical charge radius
L	length of elongated charge
p_c	explosion pressure in cavity
p_{ch}	detonation pressure in the charge
$\bar{\gamma}_s$	specific weight of explosive substance
γ_r	specific weight of rock
$\bar{\gamma}$	density of charge = W/V
τ	characteristic resistance stress of rock in simplified equilibrium model
λ	propagation factor for pressure wave in rock
λ_s	propagation factor for pressure wave in rock with spherical propagation
λ_s	propagation factor for pressure wave in rock with cylindrical propagation

k specific heat ratio

β proportionality constant in empirical crater formula

f_d decoupling factor for country rock = relationship of h_o with and without decoupling